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UNITED STATES NAVAL POSTGRADUATE SCHOOL

THESIS

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GUIDANCE FOR COMMANDERS IN ESTABLISHING CHEMICAL-BIOLOGICAL DEFENSIVE POLICIES

by

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ABSTRACT

Soldiers wearing chemical-biological (CB) protective uniforms experience heat stress and may become heat casualties. Current defensive doctrine suggests that commanders may reduce the risk of heat casualties by rotating their troops through varying degrees of protection. Since unprotected troops will become CB casualties if an attack occurs, the commander must trade risk of heat casualties for risk of CB casualties. The effects of temperature and work rate on the buildup of heat in protected soldiers are examined. The problem facing the commander is formulated as a queueing theory problem and a computer simulation used to obtain a solution. Graphs show the percent of unprotected personnel within a unit necessary to prevent heat casualties for a range of temperatures and unit work rates.

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CHAPTER I

INTRODUCTION

1.1 Statement of the Problem

Modern chemical and biological weapons systems present an extreme hazard to troops operating on the battlefield of the future. The characteristics of these weapons are such that personnel may not even be aware that they are being attacked until casualties occur. Therefore defensive policies require that commanders take steps to protect their personnel before an attack or when an attack appears imminent. Such policies demand a high degree of chemical and biological (CB) defensive readiness when the intelligence situation indicates enemy use of CB weapons is probable. Since defensive measures include wearing of protective uniforms by troops, commanders are faced by a serious dilemma. This dilemma occurs because wearing the CB protective uniform results in heat stress to the protected individuals.

Current defensive policies suggest that a commander may overcome his problem by adopting various levels of protection within his unit or by mixing the degree of protection that he prescribes to his unit. However, very little guidance is available to help the troop commander decide what portion of his unit should be highly protected and what portion should be less protected.

The purpose of this work is to provide quantitative guidance for two defensive policies available to a commander. Heat stress relationships and the principles of queueing theory are used to determine how many persons must remain unprotected at all times if heat casualties are to be minimized. The number of protected and unprotected personnel necessary to prevent heat casualties is calculated for different climatic

conditions and for different work levels. Based on the results obtained here a commander can evaluate the feasibility of these two defensive plans for his unit's operations. A plan which requires more unprotected personnel than the unit could afford to lose from CB casualties should not be implemented.

1.2 Background

When the use of chemical agents was initiated during World War I, units were immediately aware when they came under a chemical attack. Chemical agents of that time, such as chlorine, phosgene, and mustard gases, were readily identifiable by their odor or visibility. Units could take necessary protective measures when and only when they came under attack. However, the current arsenal of chemical weapons does not generally provide any sensory warning. For example, the majority of nerve agents are colorless and odorless. Furthermore, these agents are lethal in such small quantities that fatal dosages may enter the body of an individual without his knowledge. The threat of such weapons together with that of biological agents, which cannot be detected by the human senses, requires either prior warning of an attack or some degree of protection at all times to minimize casualties.

Chemical and biological protective uniforms are available which act as a barrier against penetration of CB agents to the soldier's body. The standard uniform, according to the Department of the Army,[4] consists of a protective mask and hood, specially treated boots, and chemical protective clothing outfit. This latter ensemble consists of trouser and shirt liners, socks, and gloves which have been chemically treated to prevent penetration of CB agents. This uniform will be issued to troops operating behind the brigade rear boundary. Troops forward of

this area will receive a two piece overgarment now under development for protection. These uniforms, while providing the necessary protection against toxic agents, also restrict the release of heat from the body of protected personnel. Data on the heat transfer capability of the standard uniform is given by Cresthull(3). The failure of CB protective uniforms to liberate all heat generated by the soldier limits activity and the time the uniform may be worn. Heat buildup in the soldier's body can produce heat prostration or heat stroke.

The problem of heat stress among soldiers wearing the CB protective uniform has been studied by Goldman and Cresthull. Goldman(6) considered the allowable working times of protected troops wearing the now Standard B (limited usability) protective uniform. This uniform consisted of normal field clothing impregnated with chemical compounds and was more resistant to heat transfer than the current uniform considered here. Dr. Goldman asserts that only minor heat stress problems will occur below effective temperatures of 70 degrees, and he gives predicted working times until a unit will have 50% heat casualties at temperatures from 60 to 100 degrees. Cresthull(3) examined the heat transfer capabilities of various protective uniforms and determined allowable safe working times for protected personnel. His work also considered what percent of each hour soldiers in protective uniforms could conduct light, moderate, or heavy work and still maintain heat equilibrium. These papers tell how long an individual can wear the CB protective uniform without becoming a heat casualty. However, more important to a commander in the field might be the questions of how long will it be necessary for each individual to wear the uniform, and can he wear it that period of time without becoming a heat casualty?

Current concepts of individual CB protective policy realize that all unit personnel cannot safely wear protective clothing at all times. Defensive doctrine as set forth by Department of Army[4] establishes three levels of Mission Oriented Protective Posture. The minimum level of protective posture calls for soldiers to wear the normal duty uniform and carry their protective masks, hoods, and gloves. At a medium level posture, troops should wear protective uniforms but carry masks, hoods, and gloves. The maximum level of posture consists of troops fully dressed in all items of the CB protective uniform. Commanders are charged with the responsibility of selecting the level of Mission Oriented Protective Posture applicable to their unit's operations. It is suggested that a commander may reduce the hazards of heat stress by mixing the levels of protective posture among members of his unit or by rotating troops to different levels of Mission Oriented Protective Posture in order to provide a relief from the buildup of body heat.

1.3 Scope

This paper is concerned with the aspects of this latter idea. Is it feasible for the commander to rotate his personnel through various levels of protective posture? Given the allowable time an individual can wear the CB protective uniform, how many personnel should be at the minimum level of protective posture to prevent heat casualties in the unit? Chapter II considers two possible options available to the commander and the heat stress considerations of each. Chapter III discusses a model which was used to determine the number of unprotected personnel necessary to prevent heat casualties. Chapter IV presents results obtained from the use of this model considering various unit work levels

and climatic conditions. The methodology and results of this thesis make possible more quantitative guidance to commanders faced with the problem of establishing CB defensive postures for their units.

CHAPTER II

HEAT STRESS ASPECTS OF THE PROBLEM

2.1 Command Considerations

The chief concerns of any commander must be the accomplishment of his mission and the welfare of his personnel. The ideal CB defensive policy would provide a minimum reduction in unit effectiveness while insuring low risks to personnel from either heat stress or CB weapons. Rotating unit personnel to different levels of Mission Oriented Protective Posture as suggested in (4) may give a commander his best opportunity to maximize his unit's effectiveness without extreme risks of casualties. Since toxic attacks will likely be undetectable by the human senses, CB casualties can be minimized by giving maximum protection to the largest number of personnel possible. It is probable that all unprotected personnel will be casualties. Hence rational defensive policies call for the highest possible number of troops, commensurate with heat stress conditions, to be in full protective uniform. These protected personnel will be accumulating body heat according to their work level and climatic conditions. The remaining unprotected troops would be dissipating the heat loads they had accumulated while wearing the uniform.

Two defensive policies for implementing rotation of troops between protective postures are considered here. Both plans call for as many troops to receive full protection as heat stress conditions will allow. The two alternatives arise from two options the commander has on how the unprotected troops will cool themselves. One alternative would arise from a commander's desire to maintain full effectiveness of his unit. Unprotected personnel would work at the same energy level as

protected personnel. Heat dissipation would be relatively slow, but unit effectiveness would remain high. The other possible option would be for unprotected personnel to perform their same duties but at reduced energy levels, thereby speeding the cooling operation. This reduced work level would result in lower unit effectiveness. Regardless of whether the commander attempts to maintain effectiveness with the former option or accepts reduced work rates with the latter, he is faced with the problem of trading risk of chemical-biological casualties for risk of heat casualties. Therefore commanders need quantitative guidance for their decision making. Information available in this thesis allows commanders to determine the number of troops which must remain unprotected and vulnerable to CB attack in order to prevent heat casualties within his unit. The remainder of this chapter discusses the factors which must be considered in evaluating the heat stress which will occur in units protected from CB agents. These considerations will be used in Chapter III to formulate a queueing theory model for solution of the problem.

2.2 Heat Stress Considerations

According to Belding and Hatch[1], heat stress occurs when an individual produces more body heat than he can release into the surrounding environment by evaporation. Heat loss by evaporation is dependent on radiation and convection heat loss and the individual's metabolic heat load. Their work provides a detailed explanation of methods for determining heat loads, and its concepts served as a basis for all heat stress calculations of this paper. Personnel wearing the full CB protective uniforms are severely restricted in the amounts of heat that they can release. Evaluation of the heat load which will be

accumulated by troops requires the knowledge of three factors: climatic conditions, heat loss capabilities of personnel in protective uniforms, and metabolic heat production rate.

2.3 Climate Considerations

The factors of weather which affect heat stress calculations include the temperature, relative humidity, wind speed, and solar heat load. The joint effects of these factors may be stated in terms of the Wet Bulb Globe Temperature (WBGT) index. This method of stating effective temperatures is well known by military personnel and is described in TB Med 175[5]. According to Goldman[6] there should be few heat stress problems below effective temperatures of 70 WBGT. Effective temperatures from 50 to 100 WBGT were studied here.

2.4 Considerations of Heat Loss in Protective Uniforms

The maximum hourly heat loss of individuals wearing protective uniforms is a function of the effective temperature. Cresthull[3] presents heat loss data for a wide variety of uniforms. Using his data, equations for maximum hourly heat loss were obtained. Troops wearing the standard protective uniform described in paragraph 1.2 with masks, hoods, and gloves have a heat loss rate, L, given by

$$L = 3.5(127\text{-}WBGT). \qquad (1)$$

The heat loss rate for individuals wearing the normal fatigue field uniform without mask, hood, and gloves is

$$L = 3.84(172\text{-}WBGT). \qquad (2)$$

Therefore personnel who are maintaining maximum Mission Oriented Protective Posture will have heat loss rates given by equation (1), and those at a minimum posture will lose heat according to equation (2).

2.5 Heat Production Considerations

Since the CB protective uniform reduces the amount of heat its wearer may liberate to the environment, a portion of the metabolic heat produced is stored in the body. The rate at which troops work is therefore an important factor in determining how long they may safely wear the protective uniform. Work at high energy levels may in fact produce more metabolic heat than can be liberated even in normal fatigue uniforms. Estimates of the heat produced at various energy levels are given by Belding and Hatch[1] as follows:

Light Work	100-150 Kcal/hr.
Moderate Work	150-300 Kcal/hr.
Heavy Work	300-550 Kcal/hr.

These estimates apply for a 154 pound man and will vary depending on the physical characteristics of personnel. Light work may include activities such as desk work, operating sighting mechanisms, or driving a vehicle. Moderate work is represented by heavy arm and leg movements or moderate lifting and pushing. Pick and shovel work or loading and stacking ammunition are examples of heavy work.

One obstacle in determining the heat casualty hazard to an entire unit of troops arises from the wide range of activities occurring within the unit. Radio-telephone operators may be performing light work at the same time that other soldiers are digging field fortifications. However, heat stress calculations for the entire unit may be

made by finding an effective metabolic heat production rate. For the purposes of this paper, the mathematical expectation of the unit's work is used.

For example, if an artillery battery conducting a fire mission has 30% of its personnel performing light work, 46% moderate work, and 24% heavy work, its effective heat production rate, P, is

$$P = .3(150) + .46(300) + .24(550) = 315 \text{ Kcal/hr.}$$

Knowledge of a unit's table of organization and the duties performed by its personnel will allow calculation of an effective work rate for a variety of unit missions.

2.6 Prevention of Heat Casualties

According to Cresthull[3] the probability of heat casualties in soldiers who have stored a heat load of 160 Kcal. is 0.5. For individuals with a stored heat load of 80 Kcal. the probability of heat casualties is zero. Therefore a chemical-biological defensive policy which attempts to minimize heat casualties should offer high probability that stored heat loads do not exceed 80 Kcal. Ideally, individuals who have stored 80 Kcal. should be allowed to remove the uniform immediately and remain unprotected until they have dissipated their stored heat load. However, such a strict policy would likely be impossible to implement under field conditions. In order to establish a reasonable defensive policy for use in this thesis, Cresthull's data was analyzed to determine a plan which gave low probability of heat casualties. A defensive policy offering 95% assurance that individuals will wait less than 15 minutes to remove the protective uniform (after storing 80 Kcal.) provides an acceptable and real world risk of heat casualties.

2.7 Calculation of Unit Cooling Requirements

The number of persons within a unit wearing protective uniforms who will reach a stored heat load of 80 kcal. during a given time period is a random variable. Values which the random variable assumes are dependent on the unit's effective heat production rate and the effective temperature. The average rate at which personnel reach 80 Kcal., i.e., the mean of the random variable, may be calculated as follows. Consider a 100 man unit working in the CB Protective uniform. Let

X = average number of persons who reach 80 Kcal. in an hour

P = effective heat production rate, Kcal/man/hr.

L = heat loss rate, Kcal/man/hr.

Then

$$X = \frac{(100 \text{ men})(P - L)\text{Kcal/man/hr}}{80 \text{ Kcal/person}}$$

$$X = 1.25\ (P - L) \text{ persons/hour.} \qquad (3)$$

For a given effective temperature (WBGT) the value of L is found by equation (1). The effective heat production rate is calculated as discussed in paragraph 2.5. A commander's defensive system should be capable of accomodating cooling requirements which occur at a mean rate given by equation (3).

2.8 Calculation of Cooling Times

Also of importance in determining how to mix levels of protective posture within a unit is the time required for individuals to completely dissipate an 80 Kcal. heat load. This time is also a random variable dependent on work rate and effective temperature. The mean value of the cooling time may be calculated by determining the heat loss potential of

cooling individuals. If troops remove their protective uniforms and continue to work at their previous work rate, then the mean cooling time, Y is given by

$$Y = \frac{80}{(L - P)} \quad \text{hours} \tag{4}$$

where P is the effective heat production rate and L is the heat loss potential of the normal fatigue uniform given by equation (2). If in addition to removing the protective uniform, troops are allowed to reduce their heat production rate to a lower level while cooling, then the heat loss potential of all cooling personnel will be the same. If the work rate of all cooling personnel was reduced to 150 Kcal/hr, for example, cooling time becomes a constant whose value is given by equation (4) with P equal to 150 Kcal/hr.

CHAPTER III

DESCRIPTION OF THE MODEL

3.1 An Approach to the Problem

Using the information and relationships discussed in the preceeding chapter and the concepts of queueing theory, it is possible to obtain results of value to a commander who must formulate chemical-biological defensive policies. Results can be found which show what percent of a unit must remain unprotected from CB attack if low probability of heat casualties is desired. This percent of the unit which must remain vulnerable to attack is determined for a range of temperatures and unit effective heat production rates. The physical situation confronting a commander lends itself to formulation as a problem of queueing theory.

If we consider the dissipation of a stored heat load as a service provided to the individual, unprotected personnel cooling themselves become customers receiving a service at a cooling-service facility. Protected personnel may be considered as a population, each member of which will sooner or later demand cooling service at the facility. The fact that this service facility has no physical characteristics such as location or human serving attendants in no way violates the concepts of queueing theory. The number of service channels, i.e., servers, available at the facility is the number of individuals the commander authorizes to remain unprotected. Thus in deciding how many troops to risk as CB casualties, he fixes the number of servers. If he orders twenty soldiers to remain unprotected at all times for cooling purposes, the number of servers will be twenty. Service time (i.e., cooling time) is a random variable which depends on effective temperature and work rate as discussed

in paragraph 2.8. Personnel accumulate 80 Kcal. heat load at a mean rate which is determined as outlined in paragraph 2.7 and then become a customer demanding cooling service.

Customers who require cooling service when all of the service channels are busy enter a queue and wait until a server becomes free. When a cooling soldier has lost his heat load, he then puts on a protective uniform and frees a theoretical service channel, which is then taken by the first soldier waiting in the queue. This latter soldier then initiates his cooling service by removing his protective uniform. For a fixed temperature, work rate, and number of servers, it is possible to determine the queueing time for individuals passing through the system. If for a given set of conditions, 95% of the customers wait for less than 15 minutes in the queue, then the defensive policy associated with these conditions is acceptable as discussed in paragraph 2.6. If on the other hand, large numbers of persons wait over 15 minutes, the commander should authorize more servers, i.e., unprotected soldiers, to prevent heat casualties. Hence this model makes it possible to determine how many unprotected personnel must be risked as CB casualties to prevent heat casualties at a given temperature and heat production rate. If this number of casualties risked is greater than the unit could accept and still perform its mission, then mixing levels of protective posture is not a feasible defensive policy for the commander to establish.

3.2 Assumptions

To obtain a solution to this queueing problem several assumptions must be made. The first assumption is that demands for cooling service occur according to a Poisson probability distribution with mean arrival

rate given by equation (3). According to Cox[2] this is likely to be a particularly good approximation if persons arriving for service come from a large population all behaving independently of one another. It appears reasonable in this case to assume that heat buildup in a soldier is independent of that in his comrades. Furthermore the number of arrivals in any time interval should be proportional to the length of the interval and independent of the number of arrivals in any other equal, non-overlapping interval. Hence there seems to be no violation of the necessary conditions for assuming a Poisson distribution.

The second assumption made is that service time has an Erlang distribution with mean service time given by equation (4). Hillier and Lieberman[7] state the Erlang distribution is very useful for approximating empirical service time distributions. Its probability distribution function,

$$f(t) = \frac{(uk)^k}{(k-1)!} \; t^{k-1} e^{-kut} \qquad j,k > 0 \qquad (5)$$

offers the capability of tailoring the distribution by varying the two parameters, u and k. There is strong intuitive appeal to the assumption that the service time distribution in this problem should have the general form of Figure 1. It is reasonable that the majority of service times will be relatively close to the mean time with small probability of extremely long or short service times. The mean cooling time is calculated from equation (4). Various combinations of the parameters were considered, and it was determined that the equation

$$f(t) = \frac{(4u)^4}{6} \; t^3 e^{-4ut} \qquad (6)$$

where u is the reciprocal of the mean cooling time, gave cooling times which appear realistic for this problem. For example, when the mean

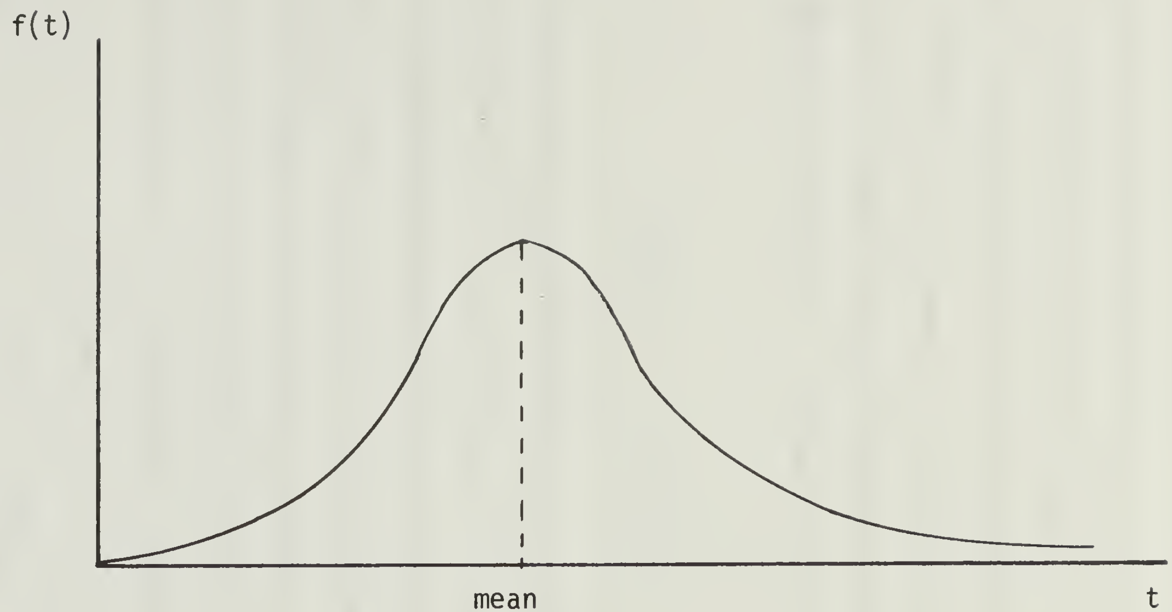

Figure 1. Service Time Distribution

cooling time is 25 minutes, the probability is 0.8 that the cooling time is greater than ten minutes and less than forty minutes. Therefore it was assumed that service time has an Erlang distribution with $k = 4$.

A final assumption is that it is possible to determine the heat load of an individual. It is assumed that soldiers know when their cooling service is finished or when they should demand cooling service. This is a condition which admittedly would be difficult or impractical to achieve in an actual field situation. However, the purpose of this paper is not to prescribe a plan for field implementation but to obtain quantitative information to assist a commander in establishing policy.

3.3 Considerations of the Queueing Problem

The problem has now been reduced to finding the queueing time distribution of a queueing system with Poisson arrivals, Erlang service times, and m servers. The number of servers necessary to insure a probability of 0.95 that queueing time is less than 15 minutes must be found for pertinent combinations of temperature and work rate. Solution of this type queueing system for the distribution of queueing time is discussed by Saaty.[9] He obtains a solution in terms of an unknown constant, and recommends experiments or other approaches to obtain the needed constant. Since information is not available to obtain an analytic solution, methods for solution by Monte Carlo techniques were adopted.

3.4 Description of the Computer Simulation

The International Business Machine Corporation's General Purpose Simulation System (GPSS) was used to simulate the queueing system. Details on the use of this simulation system are available in IBM's User Manual.[8] The GPSS program allows the user to simulate queueing

situations by generating demands for service which move through functional blocks portraying the physical characteristics of the system. The demands, called transactions, are initiated through the use of a random number generator and a probability distribution function established by the user. Transactions move through the simulated system, entering service facilities if they are free or joining waiting lines if they are not. Service facilities which have multiple servers are called storages. The user establishes the number of servers by means of a storage identification card which gives the capacity of the storage. Transactions which try to enter a full storage are sent to a queue until a vacancy exists. Queueing statistics are compiled for each transaction such as its time to transit the system, time spent queueing, and its service time. Other useful values are accumulated for queues and service facilities such as average contents, maximum contents, and average times spent by transactions in queues and service.

The flow chart of the computer simulation used is shown in Figure 2 and a sample program is in Appendix A. Block 1 calls for the generation of transactions having exponentially distributed interarrival times with a mean of A. This gives the Poisson distributed cooling demands required for this problem. The value of A is the reciprocal of the mean number of arrivals calculated by equation (3). The second block tells the transaction to go to Queue 1. If the queue is empty, the transaction attempts to go to the next block; if not it joins the waiting line. The third block instructs the transaction to enter the cooling-service facility, called COOL. If the facility is presently full, Block 3 will cause the transaction to remain in queue until a vacancy exists. When the transaction is admitted to COOL,

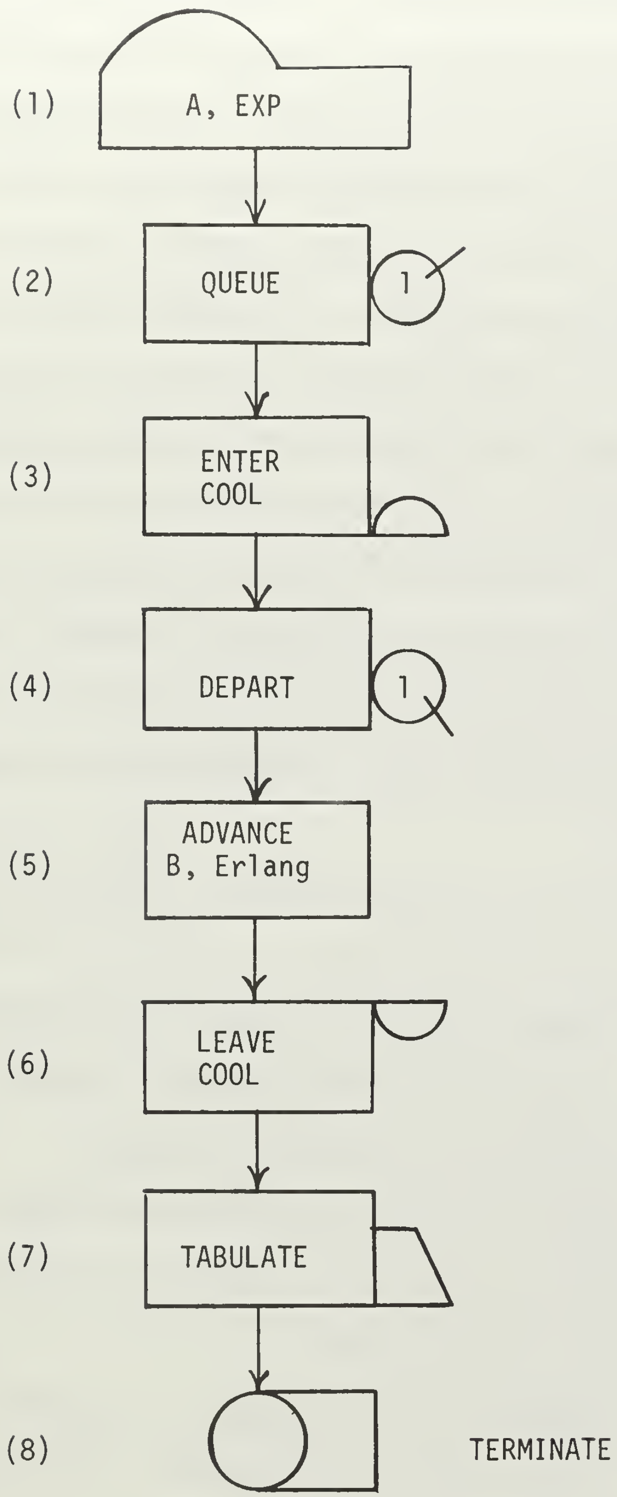

Figure 2. Simulation Flow Chart

Block 4 removes the transaction from the queue and information such as how long the transaction was in the queue is tabulated.

Block 5 provides the mechanism for simulating service time. This block holds the transaction for a period of time specified by the user. As shown, the service time will have an Erlang distribution with mean B. The value of B is calculated by equation (4). The program obtains service times from a random number generator and the probability distribution given by the user. If constant service times are desired, the function is eliminated, and the constant value only given. Transactions enter Block 6 after their service time is finished. This block registers a vacancy in COOL which can now be filled from the queue. Block 7 causes tabulation of service time data. Block 8 removes the transaction from the system and increments a counter. The simulation continues until the counter registers the number of transactions specified by the user and then stops. Program output includes the following information:

1. Maximum and average contents of service facility
2. Average service time
3. Frequency table of the number of service times falling in given time intervals. (In this case 15 minute time intervals were used.)
4. Maximum and average contents of the queue
5. Number of transactions with zero waiting time
6. Average queueing time
7. Frequency table of the number of queueing times falling in given time intervals. (15 minute intervals were used.)

3.5 Simulation Input Requirements

To conduct one simulation of the queueing system for a given temperature and work rate the following steps were taken. First the mean time between arrivals was calculated by taking the reciprocal of the mean demand rate of equation (3). This value was entered by a GENERATE instruction card. The next step required preparation of input cards which defined the service time distribution function. These identifier cards give an argument and the value of the cumulative distribution function at that argument. The program used to calculate these values for an Erlang distribution of order four is in Appendix B. The mean service time was calculated from equation (4). Finally a STORAGE definition card was entered which established the number of servers at the service facility for this iteration of the program. The simulation was initiated by a START card which specified the number of transactions which must enter the termination block before the simulation stops.

3.6 Solution Procedure

Solution of the queueing problem for the number of servers which gave 95% assurance that the queueing time of individuals was less than 15 minutes was an iterative procedure. For a given work rate and effective temperature the input requirements discussed above were calculated. A number of servers for the service facility was assumed, and the simulation for those conditions was completed. Then the output data was examined to see if the criterion discussed in paragraph 2.6 for an acceptable defensive policy had been satisfied. If the results showed that more than 5% of the transactions had queueing times that were greater than 15 minutes, the number of servers was

increased and the simulation repeated. If the number of transactions with queueing times greater than 15 minutes was less than 5%, results with fewer servers were examined. This procedure was repeated until the smallest number of servers which gave queueing times of less than 15 minutes to 95% of the transactions was obtained. Results of the simulation are discussed in the following chapter.

CHAPTER IV

RESULTS

4.1 Results for Constant Cooling Times

One of the two defensive policies discussed in paragraph 2.1 called for personnel who remove the protective uniform for cooling service to also reduce their work rate. This plan, while reducing the unit's effectiveness, should also reduce cooling time. To obtain solutions for this defensive policy all personnel were considered to reduce activity to a light work rate of 150 Kcal/hr. while receiving cooling service. In this situation service time would be constant for all services given. The simulation for this defensive plan was based on a unit consisting of 100 soldiers, and hence the acceptable number of servers converted directly to percent unprotected personnel. Solutions were obtained from the simulation for effective temperatures ranging from 50 to 100 degrees WBGT. Unit expected heat production rates of 200, 300, 400, and 500 Kcal/hr. were considered. The results of the simulation are shown in Tables I through IV. Figure 3 is a graph showing the percent of the unit which must be unprotected to prevent heat casualties versus effective temperature.

Using Figure 3 a commander can evaluate the feasibility of this defensive plan for his unit. Suppose a commander estimated the effective heat production rate of his unit was 200 Kcal/hr. If he was operating in an effective temperature of 70 degrees WBGT, Figure 3 shows that 12% of his troops must remain unprotected for cooling in order to prevent heat casualties. If the commander feels that he can accept the risk of 12% CB casualties, this defensive policy may be considered feasible.

Table I. Summary of Results, Constant Cooling Time, Work Rate of 200 Kcal/hr.

Effective Temp. (WBGT)	Heat Loss Kcal/man/hr	Heat Stored Kcal/man/hr	Mean Arrival rate persons/hr	Cooling time Minutes	Number of Servers Required
50	235	0	No Heat	Buildup	0
60	205	0	No Heat	Buildup	0
65	188	12	14	18	6
70	174	26	33	20	12
80	145	55	72	24	28
90	113	87	101	29	52
95	98	102	129	33	68

Table II. Summary of Results, Constant Cooling Time, Work Rate of 300 Kcal/hr.

Effective Temp. (WBGT)	Heat Loss Kcal/man/hr	Heat Stored Kcal/man/hr	Mean Arrival Rate persons/hr	Cooling Time Minutes	Number of Servers Required
50	235	65	85	15	22
60	205	95	120	17	33
65	188	112	138	18	41
70	174	126	156	20	50
75	159	141	170	22	61
80	145	155	200	24	76
85	128	172	212	26	89
90	113	187	240	29	100

Table III. Summary of Results, Constant Cooling Time, Work Rate of 400 Kcal/hr

Effective Temp. (WBGT)	Heat Loss Kcal/man/hr	Heat Stored Kcal/man/hr	Mean Arrival Rate persons/hr	Cooling Time Minutes	Number of Servers Required
50	235	165	211	15	50
60	205	195	240	17	65
65	188	212	257	18	72
70	174	226	277	20	83
75	159	241	300	22	98
80	145	255	318	24	100

Table IV. Summary of Results, Constant Cooling Time, Work Rate of 500 Kcal/hr.

Effective Temp. (WBGT)	Heat Loss Kcal/man/hr	Heat Stored Kcal/man/hr	Mean Arrival Rate persons/hr	Cooling Time Minutes	Number of Servers Required
50	235	265	328	15	75
55	220	280	340	16	85
60	205	295	360	17	90
63	190	310	390	17	98
65	188	312	400	18	100

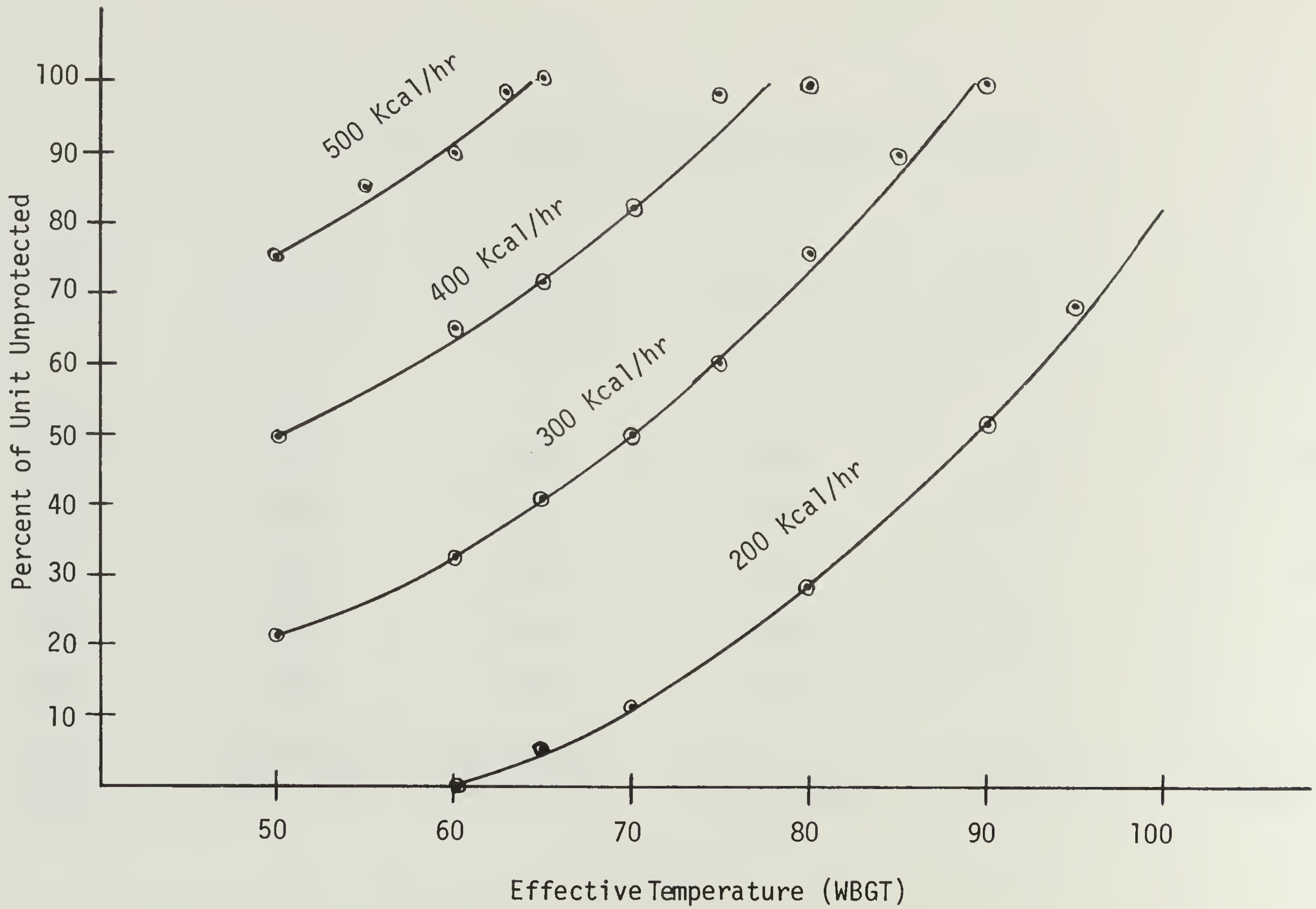

Figure 3. Unprotected Troops Necessary to Prevent Heat Casualties, Constant Cooling Time

On the other hand, if his unit's effective heat production rate was 300 instead of 200 Kcal/hr., the graph indicates 50% of his unit must remain unprotected. In this case the plan would most likely be rejected as infeasible since now half of the troops are vulnerable to CB attack.

4.2 Results for Variable Cooling Times

The other defensive plan discussed in paragraph 2.1 attempts to maintain unit effectiveness by having all personnel work at their normal work rates. When the time arrives for a soldier to dissipate his heat load, he removes the protective uniform but continues his same work rate in the normal fatigue uniform. Consequently, the metabolic heat production rate of cooling personnel is the same as that of the rest of the unit's troops. This results in the cooling times being a random variable, which was assumed to have an Erlang distribution. Unit effectiveness remains unchanged, but cooling service times are increased for this defensive policy. As in the previous case with constant cooling times, solutions were obtained by simulation for work rates of 200, 300, 400, and 500 Kcal/hr. Results for 200 and 300 Kcal/hr. rates are given in Tables V and VI. All results for 400 and 500 Kcal/hr. showed that 100% of the unit must be unprotected. Also at these high work rates heat buildup can occur in the fatigue uniform. Figure 4 is a graph of necessary percent of personnel unprotected versus the effective temperature.

The results for both constant and variable cooling times are conservative values for the percent of persons which must remain unprotected to prevent heat casualties. As such they may present a pessimistic picture of the actual cooling requirements which will exist in actual field situations. This is true because a constant mean rate of cooling demands was used for any given set of temperatures and work rates. This

Table V. Summary of Results, Variable Cooling Times, Work Rate of 200 Kcal/hr.

Effective Temp. (WBGT)	Heat Loss Kcal/man/hr	Heat Stored Kcal/man/hr	Mean Arrival rate persons/hr	Cooling time Minutes	Number of Servers Required
50	235	0	No Heat	Buildup	0
60	205	0	No Heat	Buildup	0
65	188	12	14	23	8
70	174	26	33	25	17
75	159	41	50	28	26
80	145	55	72	31	40
85	128	72	90	36	58
90	113	87	101	40	70
95	98	102	129	50	100

Table VI. Summary of Results, Variable Cooling Times, Work Rate of 300 Kcal/hr.

Effective Temp. (WBGT)	Heat Loss Kcal/man/hr	Heat Stored Kcal/man/hr	Mean Arrival rate persons/hr	Cooling time Minutes	Number of Servers Required
50	235	65	85	29	41
55	218	82	103	32	58
60	205	95	120	37	72
65	188	112	138	43	94
70	174	126	156	51	100

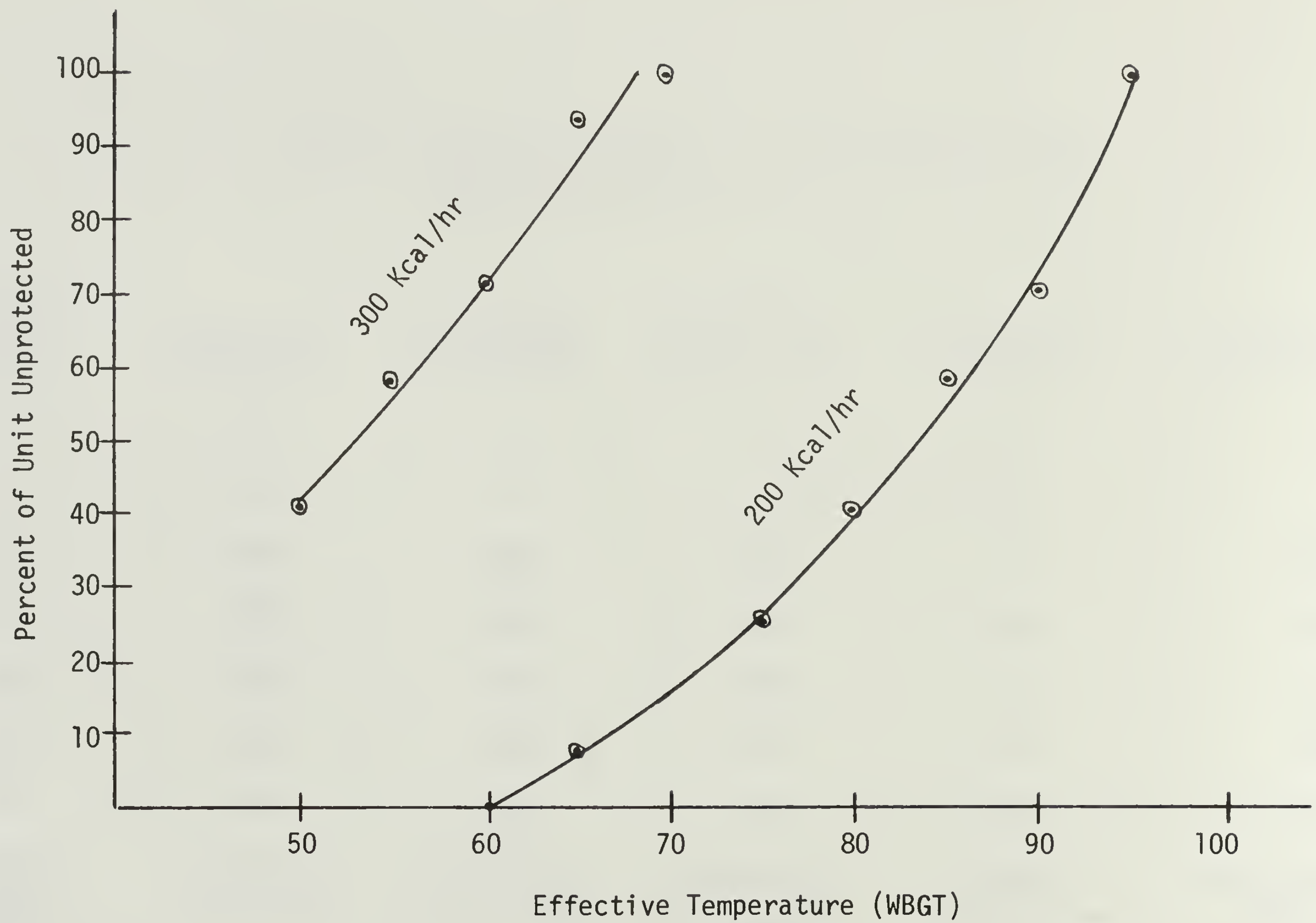

Figure 4. Unprotected Troops Necessary To Prevent Heat Casualties, Variable Cooling Time

is not completely realistic since the mean rate of cooling demands will decrease as more and more soldiers enter the cooling facility and are therefore not available to create new demands on the system. Sensitivity analyses, which are discussed in the next section, were conducted to determine the effects of errors in demand rate and other simulation parameters. It appears that this lack of realism assumes importance only at high temperatures and work rates where the number of unprotected personnel is extremely high. Under such conditions small variations in the number of unprotected personnel will not greatly influence the commander's decisions.

4.3 Stability and Sensitivity Analyses

Each solution obtained for the various temperatures and work rates was based on results of the computer simulation representing 500 transits of the queueing system. Since the demand rate and the service times varied between iterations of the simulation, the real times represented by 500 transactions varied widely. The average time represented by 500 transactions was 11.5 hours of operation of the queueing system. A stability analysis was made to determine the effect of the number of transactions on the results. Results from simulations using 1000 and 5000 transactions varied less than 3% with those using 500 transactions. Hence it appeared steady-state results were obtained from 500 transactions, and this value was used for all solutions.

Sensitivity analyses were also conducted to determine the effects of changes in mean demand rate for cooling and mean service time on solutions. Changes of 10% in the mean demand rate for cooling produced an average change of 14% in the number of unprotected personnel. When 10% variations in the mean cooling times were introduced, results varied an average of 21%.

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 Summary

Modern chemical-biological (CB) weapons systems will produce high casualties among unprotected troops. Defensive policies require commanders to protect their personnel when CB attacks are imminent. Protective measures include wearing protective uniforms which cause heat buildup in the wearer's body. This heat stress presents the threat of heat casualties among protected personnel. Current defensive doctrine suggests this threat may be reduced by rotating troops through various degrees of protection. Some portion of a unit may be protected and storing a heat load, while the remainder is unprotected and dissipating their stored heat load. Two defensive policies are examined to determine how many troops must remain unprotected and cooling in order to prevent heat casualties.

Heat buildup in soldiers wearing the protective uniform depends on weather conditions and the soldiers' metabolic heat production rate. Heat transfer capabilities of the protective uniform may be calculated for given effective temperatures (WBGT). How often a soldier will require cooling can be determined from his heat storage rate, i.e., heat produced minus heat lost. Cooling requirements for an entire unit may be made by calculating the unit's effective heat production rate. Individuals within the unit should begin cooling themselves as soon as their stored heat load equals 80 Kcal. to prevent heat casualties. A defensive policy offering 95% assurance that soldiers wait less than fifteen minutes to begin cooling provides an acceptable risk of heat casualties.

Knowledge of the unit's effective heat production rate and the effective temperature can be used to calculate the average number of requirements for cooling the unit can expect per hour. Likewise it is possible to calculate how long soldiers will require to dissipate their heat load. Using this information and the concepts of queueing theory, results showing how many troops must remain unprotected at all times to prevent heat casualties were obtained. Soldiers who are unprotected are considered to be customers receiving cooling service from a capacity-limited service facility. Protected soldiers will demand service as soon as they store 80 Kcal. The capacity, i.e., number of servers, of the service facility is determined by the number of unprotected soldiers the commander authorizes.

Personnel who require cooling service when the service facility is filled join a queue. If the queueing time of at least 95% of the persons who must wait is less than 15 minutes, the authorized number of unprotected soldiers is adequate. Demands for cooling are assumed to arrive according to a Poisson probability distribution. Cooling service times are assumed to be Erlang distributed. Solution for the required number of unprotected personnel to prevent heat casualties is obtained by solving the queueing system for the number of servers necessary to insure a 0.95 probability that queueing time is less than 15 minutes. A computer simulation was used to solve the problem for temperatures of 50 to 100 degrees (WBGT) and unit effective heat production rates of 200, 300, 400, and 500 Kcal/hr. Graphs showing the required percent of unprotected personnel (number of servers) versus effective temperatures are used to present results. Commanders may then determine how many unprotected troops they must risk as chemical-biological casualties if they wish to reduce the threat of heat casualties by rotating their personnel through various degrees of protection.

5.2 Conclusions

The results of this work give commanders quantitative guidance in implementing current suggested chemical-biological defensive policy. The commander, who wishes to minimize the danger of heat casualties by rotating his personnel through different levels of Mission Oriented Protective Posture, can see the risks involved. He can see if the number of unprotected personnel necessary to prevent heat casualties exceeds the CB casualties he could accept and still accomplish his mission. The results show that in most cases the risk of CB casualties must be high in order to provide an acceptable risk of heat casualties. Thus the feasibility of the whole concept of Mission Oriented Protective Posture is suspect if judged solely on its capability to minimize heat casualties.

Perhaps more important than the actual results obtained is the methodology developed here. Previous work has considered the length of time individuals can tolerate the protective uniform. Use of the procedures developed here can provide more definitive guidance to commanders on how these tolerable time limits satisfy requirements of operations in the field.

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APPENDIX A

```
//JOBLIB DD     DSNAME=GPSS,DISP=(OLD,PASS)
//            EXEC GPSS,TIME.GO=5
//GO.SYSIN DD  *
*
*          TEMP=60    CALORIES=300
*
 EXPON FUNCTION    RN1,C24
0     0      .1     .104  .2     .222  .3     .355  .4     .509  .5     .69
.6    .915   .7     1.2   .75    1.38  .8     1.6   .84    1.83  .88    2.12
.9    2.3    .92    2.52  .94    2.81  .95    2.99  .96    3.2   .97    3.5
.98   3.9    .99    4.6   .995   5.3   .998   6.2   .999   7.0   .9997  8.0
  ERLG FUNCTION    RN2,C23
0     0      .0023  300   .0245  600   .0823  900   .1742  1200  .2879  1500
.4088 1800   .5250  2100  .6290  2400  .7171  2700  .7888  3000  .8452  3300
.8883 3600   .9205  3900  .9441  4200  .9611  4500  .9732  4800  .9817  5100
.9876 5400   .9917  5700  .9944  6000  .9963  6300  .9976  6600
*
 COOL  STORAGE     70
     1 QTABLE      1,0,900,24
 STIME TABLE       ST1,0,900,24
*
       GENERATE    30,FN1
       QUEUE       1
       ENTER       COOL
       DEPART      1
       ADVANCE     1,FN$ERLG
       LEAVE       COOL
       TABULATE    STIME
       TERMINATE   1
       START       500
       CLEAR
 COOL  STORAGE     71
       START       500
       CLEAR
 COOL  STORAGE     72
       START       500
       CLEAR
 COOL  STORAGE     73
       START       500
       CLEAR
 COOL  STORAGE     74
       START       500
       END
```

APPENDIX B

```
//      EXEC    FORTCLG
//FORT.SYSIN    DD   *
      DIMENSION   A(100),B(100),XMU(10),YMU(10)
      READ 1, NUM
    1 FORMAT  (I2)
      DO 3   I=1,NUM
      READ 2, YMU(I)
    2 FORMAT (F10.3)
    3 CONTINUE
      DO 5   I=1,NUM
      XMU(I)=1.0/YMU(I)
    5 CONTINUE
      DO 50   N=1,NUM
      T=0.0833
      INA=(YMU(N)*3.)/T
      DO 20   I=1,INA
      SS1=4.0*XMU(N)*T
      SS2=(SS1*SS1)/2.
      SS3=(SS2*SS1)/3.
      SUM=SS1+SS2+SS3+1.0
      X=EXP(SS1)
      X1=SUM/X
      Y=1.0-X1
      A(I)=T*3600.
      B(I)=Y
      T=T+0.0833
      Z=YMU(N)*3600.
   20 CONTINUE
      PRINT 21,   Z
   21 FORMAT (//,5X,'MU = ',F10.0,//)
      DO 30   I=1,INA
      PRINT 22, A(I), B(I)
   22 FORMAT  (10X,'T = ',F10.0,5X,'F(T) = ',F10.4)
   30 CONTINUE
   50 CONTINUE
      END
```

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13. ABSTRACT

Soldiers wearing chemical-biological (CB) protective uniforms experience heat stress and may become heat casualties. Current defensive doctrine suggests that commanders may reduce the risk of heat casualties by rotating their troops through varying degrees of protection. Since unprotected troops will become CB casualties if an attack occurs, the commander must trade risk of heat casualties for risk of CB casualties. The effects of temperature and work rate on the buildup of heat in protected soldiers are examined. The problem facing the commander is formulated as a queueing theory problem and a computer simulation used to obtain a solution. Graphs show the percent of unprotected personnel within a unit necessary to prevent heat casualties for a range of temperatures and unit work rates.

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